

# Embedded Electrostatic Sensors for Mars Exploration Missions

C.I. Calle<sup>1</sup>, J.G. Mantovani<sup>2</sup>, C.R. Buhler<sup>3</sup>, E.E. Groop<sup>1</sup>,  
M.G. Buehler<sup>4</sup>, and A.W. Nowicki<sup>5</sup>

<sup>1</sup>Electrostatics and Materials Physics Laboratory, NASA  
Kennedy Space Center, FL 32899, USA  
phone (1) 321-867-3274  
email: carlos.i.calle@nasa.gov

<sup>2</sup>Department of Physics and Space Sciences, Florida Institute of Technology  
150 West Boulevard  
Melbourne, FL 32901, USA  
email: jmantova@fit.edu

<sup>3</sup>Swales Aerospace  
Kennedy Space Center, FL 32899  
email: buhlecr@kscems.ksc.nasa.gov

<sup>4</sup>Jet Propulsion Laboratory, California Institute of Technology  
4800 Oak Grove Drive  
Pasadena, CA 91109  
email: martin.g.buehler@jpl.nasa.gov

<sup>5</sup>ASRC Aerospace  
Kennedy Space Center, FL 32899  
email:

***Abstract***—Instrumentation on NASA's Mars landers have shown that winds air-lift dust-size grains of iron-rich clays which are the weathering products of the abundant iron- and magnesium- rich volcanic rocks commonly found on the Martian surface. Experiments conducted at Arizona State University and at NASA Ames Research Center, as well as similar experiments in our laboratory, suggest that when these dust particles are transported by the wind, they collide and develop electrostatic charges. It has been suggested that sand-size particles on the surface could be aggregates of dust particles bound to each other by electrostatic forces. This paper describes the design of electrostatic sensors embedded in different materials commonly used in planetary spacecraft and their possible use in future exploration missions to the planet.

## I. INTRODUCTION

Early experimental work by Eden and Vonnegut [1] suggested that dust motion could be a source of electrostatic charge in the dry Martian atmosphere. Dust devils, observed with daily frequency during the successful Mars Pathfinder mission, agitate dust particles airlifted into the atmosphere by an as yet unknown mechanism. Dust storms, occurring less frequently, move these particles across large distances. Contact electrification (triboelectrification) of these particles in chaotic motion should occur. It is also believed that incident UV radiation should electrify particles floating in the atmosphere or resting on the surface [2]. Electrostatic charging of dust and sand particles on Mars is exacerbated by the low humidities of the atmosphere near the dry surface. It has even been suggested that the formation of soil agglomerates and sand dune formation may be attributed to the electrostatic properties of the Martian soil [3].

The triboelectric properties of particulate materials have been shown to be functions of the bulk mineralogical composition, condition of the surfaces (radiation damage, oxidation, ions, adsorbed substances, contamination, and impurities), particle size and shape, state of electrostatic charge prior to contact, force of contact, and environmental conditions such as temperature, pressure, atmospheric composition, and humidity [4,5]. Despite the number of variables affecting triboelectric charging, a variety of studies have shown that different minerals can be differentiated based on their triboelectric behavior and placed in a triboelectric series [6-8]. This triboelectric series places materials in order of how they respond electrostatically when in placed in contact with one another. Even though some experimenters derive slightly different triboelectric series, there is a general consensus among the placement of common materials, including minerals.

To date, there has been no experiment on the surface of Mars to directly measure either the amount of charge contained on the surface dust and soil particles or on the strength of the atmospheric electric fields that airborne dust might generate [9].

A system of embedded sensors that can be incorporated into the wheel of any future mission rover would provide for a simple and fairly unobtrusive way to measure the distribution of electrostatic fields on the Martian surface and to measure variations in soil electrostatic response. This technology could perhaps be applied to different types of sensors that require the mobility provided by a rover's wheel. In this paper, we describe the design and construction of several prototypes of this instrument.

## II. INSTRUMENT DESIGN

### A. Parent Technology

The embedded electrostatic sensors being used in the design of the rover wheel are based on the sensors developed for a flight instrument, the Mars Environmental Compatibility Assessment (MECA) Electrometer, which was developed by the Jet Propulsion Laboratory and the Kennedy Space Center to characterize the electrostatic interaction between the surfaces of insulating materials and the soil on the surface of Mars [10]. The MECA Electrometer (Fig. 1) included five sensors in a line array with a resolution of 3 million elementary charges. The MECA electrometer has been thoroughly tested and calibrated in our laboratories under several environmental conditions, including ambient Martian atmospheric conditions [11-15]. Incorporating the MECA Electrometer technology into a wheel of the Mars Smart Lander requires no further advancement of its basic circuitry other than transferring data from the wheel to the rover. The electronic circuitry for the Wheel Electrometer is derived directly from the MECA Electrometer.

The five in-line circular patches shown in Figure 1(a) are the five types of insulators. The two openings shown above the five insulators in the electrometer photo are the local electric field sensor on the left, and the ion gauge on the right. The temperature sensor is a dedicated integrated circuit chip that is mounted inside the case, and is not shown in the photo of the MECA Electrometer.

The insulating materials on the MECA Electrometer were selected for their use on previous space missions. The five insulators selected were: Fiberglass/Epoxy, Polycarbonate (known as Lexan<sup>TM</sup>), Polytetrafluoroethylene (Teflon<sup>TM</sup>), Rulon J<sup>TM</sup>, and Polymethylmethacrylate (Lucite<sup>TM</sup> or PMMA). These insulators span the triboelectric series.

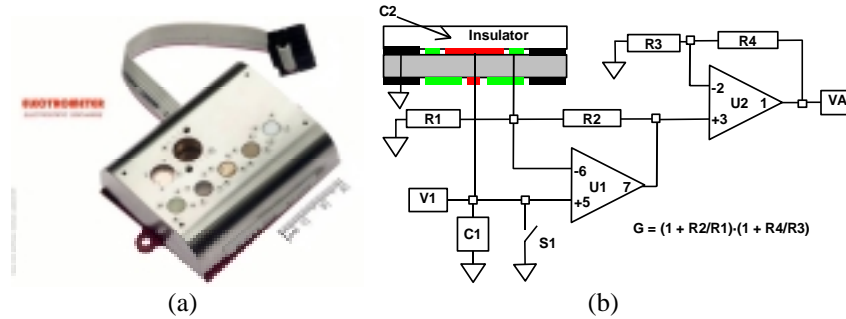


Fig. 1 (a). The MECA Electrometer showing five insulators over the triboelectric sensors (lower part), a bare electrometer (top left) and an ion gauge (top right). (b) The electrometer circuitry behind each insulator is a charge-to-voltage converter composed of C1, C2, and a switch S1 used to discharge C1.

The electrometer measures the triboelectrically-induced charge after it has been rubbed against the Martian soil and separated from the surface. The triboelectric sensor circuit has an output voltage  $V_A$  that is proportional to the electric charge that develops on the surface of the insulator. The circuit is shown schematically in Figure 1(b). The analog-to-digital converter in the MECA electrometer can detect an amount of electric charge as small as 0.5 pC, which is numerically equivalent to  $3.1 \times 10^6$  elementary charges.

### B. The Wheel Electrometer

The Wheel Electrometer System (WES) consists of a series of triboelectric and electric field sensors that might be incorporated into one of the wheels of the Field Integrated Design & Operations (FIDO) rover (see Figure 2). FIDO is an advanced vehicle that is used in technology definition and field tests for future NASA Mars Program missions [16, 17].

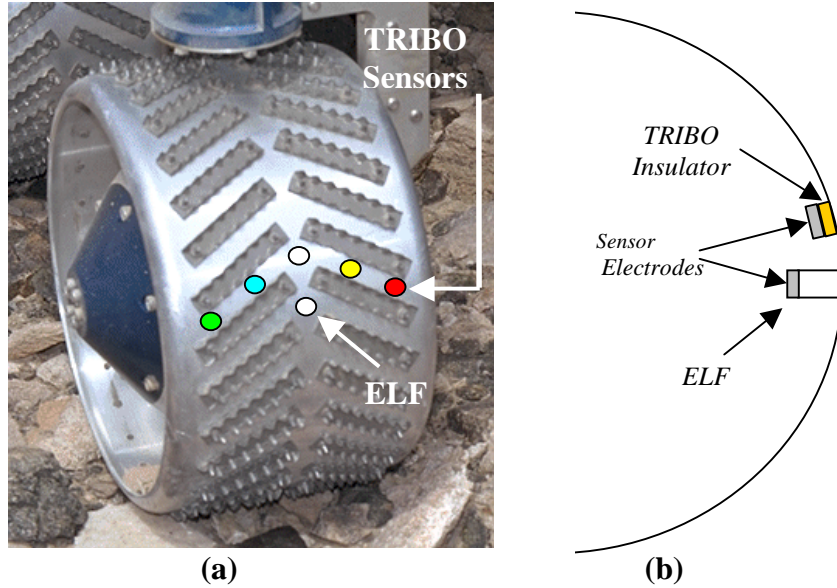


Fig. 2. (a) The Wheel Electrometer System (WES) shown on the FIDO wheel. (b) Cross-sectional view of the ELF and TRIBO modules. The ELF is recessed to allow measurement of an undisturbed soil plug that has not been compressed or rubbed by the wheel rim.

The WES will contain several sensor modules. The sensors will be attached just beneath the rover wheel in such a way that each sensor will be exposed to the Martian regolith either by line of sight through a small amount of Martian atmosphere, or by direct contact with the regolith.

There will be two basic types of sensors. The first type of sensor is the Electric Field sensor (ELF) that will measure the regolith surface charge density (charge per unit area) as the rover wheel rolls over the Martian surface. The

second type of sensor is the Triboelectric sensor (TRIBO) which will measure the amount of electrical charge that develops on a wheel-mounted insulator material through frictional contact as the rover wheel rolls over the Martian regolith.

Figure 2 (a) shows the FIDO wheel with the both the ELF and TRIBO sensor modules. It would be desirable to install the WES onto one of the front wheels of the rover, since the ELF will monitor undisturbed electric fields on the surface.

### *C. Sensor Technology*

The ELF and TRIBO sensors are actually based on the same parent technology. Each type of sensor simply measures the amount of charge that is induced on a metal electrode that has been exposed to some external distribution of electrostatic charge and has sensitivities that are achieved by adjusting circuit component values and the sensor area (Figure 1(b)) [10].

In the case of the ELF sensor, the source of the charge would be any charged soil particles that may be present on the Martian surface at the time the rover wheel rolls over it. The ELF sensor electrode will be recessed several centimeters radially inward from the outer surface of the wheel through a hole in the wheel. This will ensure that the ELF directly measures any naturally occurring charge that may be present on a small patch of undisturbed Martian regolith as the wheel rolls forward. The ELF will provide an output voltage that is directly proportional to the amount of charged regolith that the sensor “sees” through the hole. The regolith’s surface charge density will be determined using the charge measurement and the known hole area. As the rover travels across the Martian surface, the local surface charge density will be mapped using the ELF measurements. These data will provide scientists with direct measurements of the presence of electrically charged particles on the Martian surface.

The TRIBO sensor module has five independent sensors. The electronic circuitry for each sensor is identical, with a different insulator material covering the electrometer sensor electrode of each sensor. Our studies of the electrostatic properties of Martian regolith simulant JSC Mars-1 at NASA KSC indicate that the electrometer response to rubbing an insulator over the simulant will be significantly different for insulators made of Teflon, Rulon-J, Lexan, Lucite, and Fiberglass. These are the same materials selected for use in the MECA electrometer. As the rover wheel rolls over the Martian regolith, each of the five different insulators will make contact with the surface. The electrostatic response to contact charging of each insulator with the regolith will provide data regarding how the regolith fits into the triboelectric series. By making these measurements as the rover travels over the Martian surface, the TRIBO sensors will be able to provide a traverse record of electrostatic properties of the Martian regolith, properties that should fluctuate as changes in soil material properties are encountered.

### III. EXPERIMENTS

Initial experiments performed with the MECA electrometer studied the feasibility of mineral identification. Experiments on the Pathfinder indicated that when the rover wheel was dug into the surface to measure the mechanical properties of the soil, visually distinct soils exhibited different mechanical properties [18]. From these experiments, one can expect to detect different electrostatic properties as well. We performed experiments with the MECA electrometer, with a second prototype electrometer designed to approximate the contact of polymers on the wheel, and with a prototype WES.

#### A. *Experiments with the MECA Electrometer*

The MECA electrometer was rubbed repeatedly with Ottawa sand,  $17\text{ }\mu\text{m}$   $\text{Al}_2\text{O}_3$  particles, and JSC-1 Martian simulant (Fig. 3). Fig. 4 shows a comparison response of each sensor with the different granular materials. We can see that rubbing with different minerals yields different responses with each electrometer sensor. This data will be calibrated in a way such that repeated measurements over a specific mineral can give consistent results. The magnitude, shape and sign of the charge response can be classified for each mineral here on Earth and the data can be interpreted correctly once received from Mars. This will not only provide a more realistic picture of the mineral constituents of dust, but also give for the first time, a concise picture of the amount of charge associated with the Martian dust.

The method for material recognition proposed here lacks the accuracy of the soil analysis provided by the Alpha Proton X-ray Spectrometer (AXPS) on the Mars Pathfinder mission, which provided detailed chemical and mineralogical information on Martian surface materials. However, this method improves on the AXPS in that a signal can be almost instantly recognized as opposed to the hours of data acquisition required for the AXPS [19].

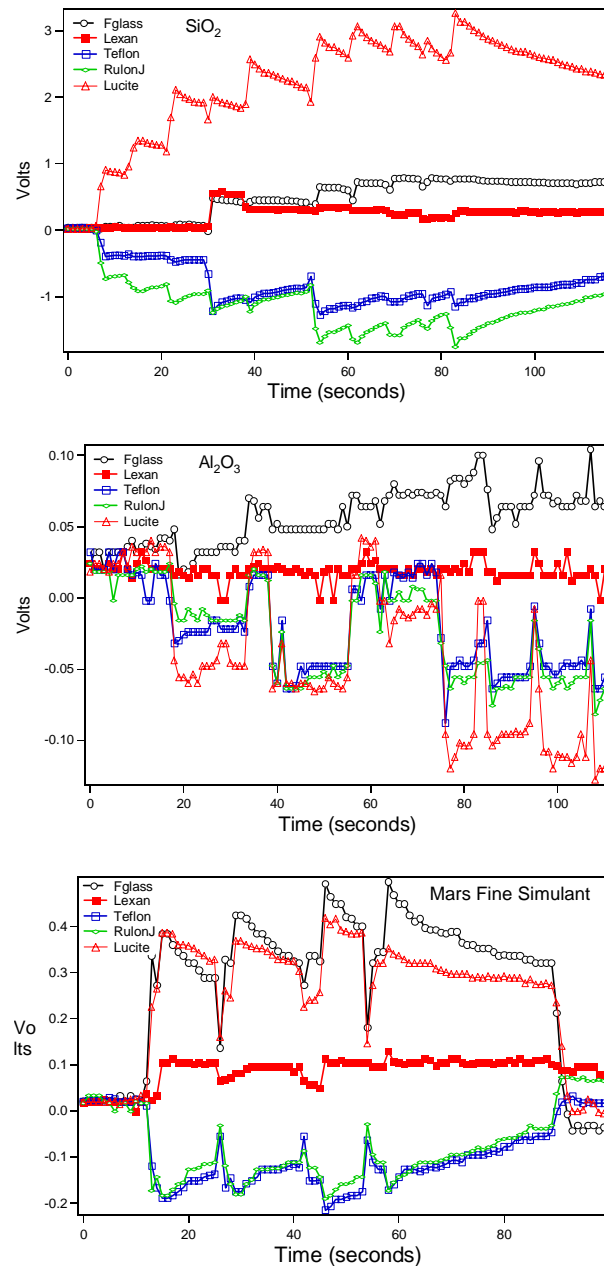


Fig. 3. Minerals rubbed with the MECA electrometer: Ottawa sand (top), 17  $\mu\text{m}$   $\text{Al}_2\text{O}_3$  particles (middle), and 5  $\mu\text{m}$  JSC Mars-1 soil simulant (bottom).



Fig. 4. Comparison of the sensors average response to the different granular materials.

### B. Experiments with a Prototype Electrometer

A second electrometer was built to test the expected performance of the WES under Martian environmental conditions in a  $\text{CO}_2$  atmosphere at  $\sim 6$  torr. This electrometer contains five sensors extending out of an electrically guarded box and are embedded inside five insulator materials: Fiberglass, Lexan, Polyethylene, Lucite, and Teflon. The electrometer was built with protruding sensors to simulate the contact and rubbing expected while the rover wheels are traversing the soil.

This electrometer was placed in contact (under its own weight of about 100 g) for approximately 3 seconds with different soil types: coarse JSC Mars-1 Martian soil simulant; coarse sand; a 50/50 mixture by volume of each; dry, coarse simulant with a 3 mm layer of 5  $\mu\text{m}$  simulant dust (to simulate weathered soil); dry, coarse sand with a similar dust layer; moist fine simulant; and moist sand. After contact, the electrometer was lifted off the surface and placed over the next material. While off the surface, the resulting charge deposited onto the insulators was measured. Fig. 5 shows the *cumulative* charge after two contacts. There were two contacts for each soil type since previous results showed that repeated contacts with the same material do not produce significant changes in the amount of charge deposited onto the insulators surface [15]. The data shown in Fig. 5 was taken without cleaning or deionizing the electrometer. These results show that the electrostatic responses with different soil types and different water content can be differentiated with this method.



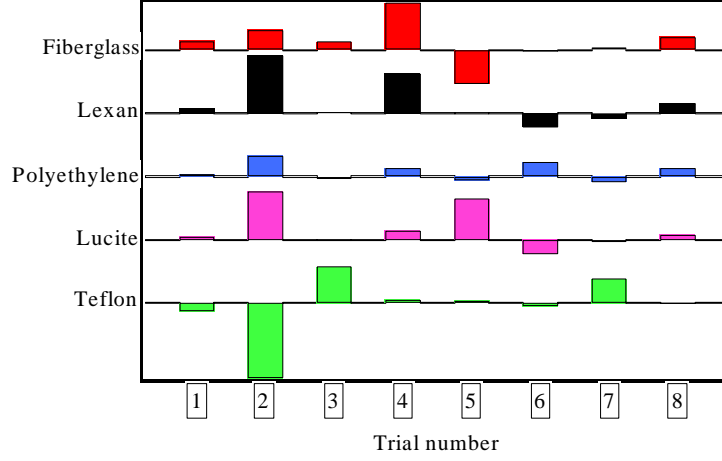


Fig. 5. Results of eight experiments performed at 6 torr CO<sub>2</sub> using the prototype electrometer. Shown is the cumulative charge deposited onto Fiberglass, Lexan, Polyethylene, Lucite, and Teflon after making two contacts with each soil surface. Conditions for the experiments are: [1] dry, coarse JSC Mars-1 Martian regolith simulant; [2] dry coarse sand; [3] a dry 50/50 mixture by volume of simulant and sand; [4] dry, coarse JSC Mars-1 simulant coated with 5  $\mu$ m simulant dust to a depth of  $\sim$ 2 mm; [5] dry coarse sand coated with 5  $\mu$ m simulant dust; [6] dry, fine simulant alone; [7] moist and [8] dry JSC Mars-1 Martian regolith simulant. The individual response of each insulator is shifted by 25 pC (or  $1.55 \times 10^8$  elementary charges).

### C. Experiments with a prototype WES

A prototype of the WES with four TRIBO sensors was built in our laboratory to test the concept in a simulated Martian environment using JSC Mars-1 simulant soil (Fig. 6). The prototype wheel is 12.7 cm in diameter and has a length of 10.3 cm. The four TRIBO sensors have a diameter of 1.84 cm with a concentric guard and a shield. The sensors are capped with Teflon, Lucite, Fiberglass/G-10, and Lexan disks of 2.0 cm in diameter and 0.7 cm thick.

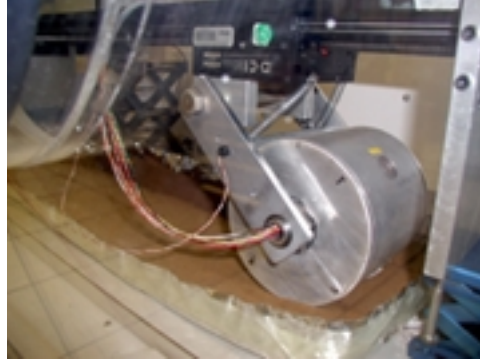


Fig. 6. Prototype Wheel Electrometer System.

Fig. 7 shows preliminary data obtained with the prototype WES in dry air at 9% relative humidity and at atmospheric pressure. The prototype wheel was rolled along a 60 cm tray containing JSC Mars-1 Simulant. The four insulators acquire different electrostatic charges when in contact with this simulant. The sharp peaks observed in the graph are due to the initial contact with the soil. Repeated contacts show an increase in the charge exchanged between simulant and insulator. Several runs were taken prior to the one generating the data presented here. The insulators and simulant were exposed to an ionizer to neutralize their surface charges before this run but no cleaning was performed. Thus, this procedure is fairly close to an actual procedure that could be used on a flight instrument. Atmospheric ions would neutralize the insulators during long periods of rover inactivity

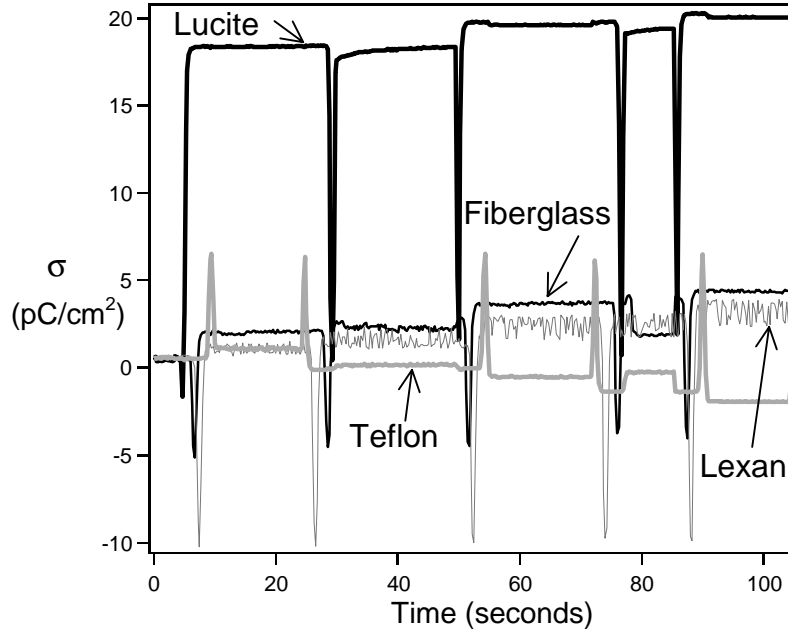


Fig. 7. Charge generated on the four polymers capping the electrometer sensors on the prototype WES.

#### D. Triboelectric Series

Triboelectric charging and subsequent processing through electric fields has been shown to be a viable method for separating ilmenite from a mixture of minerals for in situ resource utilization and oxygen production on the Moon [20]. The results of all of the referenced studies, combined with recent data presented here and the Triboelectricity Series of Polymers and Other Materials from Henniker [21], were used to construct the Triboelectric Series shown in Table 1.

TABLE 1: BASELINE TRIBOELECTRIC SERIES FOR COMMON MINERALS

<b>Positive</b>	
(Low Work Function)	
Fluorite, Cuprous Oxide, Barium Oxide	Forsterite
Microline	
Calcite, Barites	
Gypsum, Muscovite	
Copper	
Window Glass	
Lucite (Polymethylmethacrylate)	
Magnasite, Zinc Oxide, Nickel Oxide	Zircon
	Rock Salt
	Wool
Borosilicate Glass, Pyrex Glass, Fiberglass	
Cupperic Oxide, Aluminum Oxide, Hematite	Bauxite, Apatite, Magnetite, Chalcopyrite
Ilmenite	
Lexan (Polycarbonate)	
Marble, Garnet	Albite
	Augite
Hornblende	
Quartz	
Mars Fine Simulant	
Biotite, Ebonite	
Sulfur	
Selenium	
Teflon, Rulon J (Polytetrafluoroethylene)	
(High Work Function)	
<b>Negative</b>	

#### IV. CONCLUSION

We have seen that differences in soil texture, size, and shape can be detected with the prototype wheel electrometer. It is also possible to distinguish between moist and dry simulant. Fig. 5 shows the results with dry and moist simulant. Moist simulant soil was exposed to normal humid (room) air while dry simulant was baked out at temperature in excess of 150°C for several hours. The results of Fig. 5 trials 7 and 8 suggest that differences in the triboelectric signal are expected as a function of soil moisture. Moisture affects the triboelectric as well as the resistivity properties of the simulant.

The wide range of triboelectric properties of minerals shown in Table 1 indicates that identification through triboelectric analysis is viable. Future work will include a matrix of experiments whereby the electrometer sensors will be exposed to several different mineral particles typical of the various models suggested by others to describe Martian dust as well as other baseline materials

for comparison. Specimens may include fine-grained hematite, fine-grained magnetite, iron-rich clay (such as nontronite) with and without nanophase iron oxides, another phyllosilicate (such as montmorillonite), JSC-1 Mars simulant, and other palagonitic altered basalts. Triboelectric signatures for each specimen will be obtained in a simulated Mars environment. The signatures will be analyzed in order to assess the ability of the sensors to differentiate between simulant species. The sensitivity of the electrometer sensors to different species will depend on the insulator materials used for the electrometers. The best insulators for differentiating between similar minerals are those located nearby on the triboelectric series. Some iteration will be necessary to hone the sensitivity of the instrument through variations in insulator composition. In addition to obtaining the triboelectric signatures for various simulants, parametric evaluations of the effects of temperature fluctuations, variations in dust particle flux, and particle size range will be undertaken. The objective of these experiments is to verify that the electrometer sensors can provide useful information regarding the mineralogical subtleties of Mars dust composition.

#### ACKNOWLEDGMENT

The authors would like to thank Nancy Zeitlin at NASA Kennedy Space Center for project management support.

#### REFERENCES

- [1] H.F. Eden, and B.Vonnegut, "Electrical breakdown caused by dust motion in low-pressure atmospheres: Considerations for Mars," *Nature*, 280, pp. 962 (1973).
- [2] A.A. Sickafoose, J.E. Colwell, M. Horányi, and S. Robertson, "Dust Levitation in a Plasma Sheath Near a Surface" *Proceedings of the 33<sup>rd</sup> Lunar and Planetary Science Conference*, 1743 (2002).
- [3] J. Koleski, and G.B. Hillard, Electrical and Chemical Interactions at Mars Workshop, Volume I, *NASA Conference Publication 10093*, p. 9 (1991).
- [4] J. Guardiola, Rojo, V., and G. Ramos, "Influence of Particle Size, Fluidization Velocity, and Relative Humidity on Fluidized Bed Electrostatics", *Journal of Electrostatics* **37**, pp. 1-20 (1996)
- [5] A.D. Zimon, *Adhesion of Dust and Powder*, Plenum Press, New York (1969)
- [6] C. Tse-San, *Vesn. Mosk. Gos. Univ., Ser. 4, Geologiya*, **2**, p. 61 (1963)
- [7] E.M. Balabanov, "Dispersed Systems in the Electric Field of a Corona Discharge, *Doctoral Dissertation*, P.N. Lebedev Physics Institute (1953)
- [8] V.N. Glazanov, "On The Electrostatic Enrichment of Coal Fragments", *Ugletekhizdat* (1950)
- [9] W.M. Farrell, M.L. Kaiser, M.D. Desch, J.G. Houser, S.A. Cummer, D.M. Wilt, and G.A. Landis, "Detecting Electrical Activity from Martian Dust Storms", *JGR*, **104**, pp. 3795-3801 (1999)
- [10] M.G. Buehler, L.-J. Cheng, O. Orient, D. Martin, R.H. Gompf, C.I. Calle, J. Bayliss, and J. Rauwerdink "From Order to Flight in Eighteen Months: The MECA/Electrometer Case Study," *Proceedings of the 2000 IEEE Aerospace Conference*, Big Sky, Montana (2000).

- [11] J.G. Mantovani, C.I. Calle, E.E. Groop, A.W. Linville, R.H. Gompf, and M.G. Buehler, "Performance Status of the Mars Environmental Compatibility Electrometer," *Proceedings of the 38th Space Congress*, (2001)
- [12] J.G. Mantovani, Calle, C.I., E.E. Groop, and M.G. Buehler, "Studies of Surface Charging of Polymers by Indirect Triboelectrification," *Bulletin of the American Physical Society*, **46**,1165 (2001)
- [13] M.G. Buehler, L-J. Cheng, O. Orient, M. Thelen, R. Gompf, J. Bayliss, and J. Rauwerdink, "MECA Electrometer: Initial Calibration Experiments," *Electrostatics 1999, Proceedings of the 10th International Conference*, Institute of Physics Conference Series No. 163, pp. 189-196, Institute of Physics Publishing, Bristol, UK (1999)
- [14] C.I. Calle, H.S. Kim, S. Young, D. Jackson, and A.J. Lombardi, "Electrostatic Characteristics of Materials Exposed to Martian Simulant Dust Particles," *Bulletin of the American Physical Society*, **43**,1631 (1998)
- [15] C.I. Calle, C.R. Buhler, J.G. Mantovani, E.E. Groop, M. D. Hogue, and A.W. Nowicki, "Experimental Results of a Mission-Ready Triboelectric Device for Mars Robotic Missions," *Proc. Electrostatics Society of America-Electrostatics Society of Japan*, 106 (2002)
- [16] R.E. Arvidson, S. Sqyres, E. T. Baumgartner, L. Dorsky, and P. Schenker, "Rover Trials for Mars Sample Return Mission Prove Successful," *EOS Transactions, Am. Geophys. Union*, **81**, 65, (2000)
- [17] A. Trebi-Ollennu, T. A. Huntsberger, Y. Chang, E. T. Baumgartner, B. Kennedy, and P. Schenker, "Design and Analysis of a Sun Sensor for Planetary Rover Absolute Heading Detection," *IEEE Trans. Robotics and Automation*, **17** (2001)
- [18] H. J. Moore, D. B. Bickler, J. A. Crisp, H. J. Eisen, J. A. Gensler, A. F. C. Haldemann, J. R. Matijevic, L. K. Reid, and F. Pavlics, Soil-like deposits observed by Sojourner, the Pathfinder rover. *Journal of Geophysical Research*, **104**, pp. 8729-8746 (1999).
- [19] J.F. Bell, III *et al.* "Mineralogic and Compositional Properties of Martian Soil and Dust: Results from Mars Pathfinder" *Journal of Geophysical Research*, Vol. 105, No. E1, pp. 1721-1755 (2000)
- [20] T.X. Li *et al.* "Dry Triboelectrostatic Separation of Mineral Particles: A Potential Application in Space Exploration" *Journal of Electrostatics* 47, pp. 133-142 (1999)
- [21] J. Henniker, *Nature* **196**, pp. 474 (1962)